Clarkson
UNIVERSITY

WALLACE H. COULTER SCHOOL OF ENGINEERING
Technology Serving Humanity

MEMORANDUM

Subject: Progress Report 012
Chaotic LIDAR for Naval Applications: FY12 Progress Report (7/1/2013– 9/30/2013)

This document provides a progress report on the project "Chaotic LIDAR for Naval Applications" covering the period of 7/1/2013– 9/30/2013.

20150309453

William D. Jemison, Professor and Chair, PO Box 5720, Clarkson University, Potsdam, NY 13699-5720
315-268-6509, Fax 315-268-7600, wjemison@clarkson.edu

Award Information

Award Number	N000141010906
Title of Research	Chaotic LIDAR for Naval Applications
Principal Investigator	William D. Jemison
Organization	Clarkson University

Technical Section

Technical Objectives

The original proposal identified the following three tasks:

- Task 1 involves the generation and characterization of a wideband CLIDAR signal suitable for system-level experiments.
- Task 2 involves a system-level investigation into the underwater propagation/scattering characteristics of the CLIDAR signals. The investigation will be performed as a function of both optical wavelength and water turbidity (absorption and scattering) in order to determine the range resolution/accuracy and signal to noise performance that can be expected using CLIDAR.
- Task 3 involves the development of an advanced chaotic laser, or CLASER, for use as a compact and cost-effective optical source for CLIDAR. This approach integrates a laser gain medium into an OOR to produce an integrated chaotic optical source.

Progress Statement Summary

We have previously reported the development of wideband chaotic lidar (CLIDAR) signals using low-power fiber ring lasers operating at infrared wavelengths (Task 1). Multiple infrared laser configurations were designed, built, and characterized in order to determine the best configuration for frequency doubling to blue-green wavelengths. We also initiated the design and testing a frequency doubler last year. In FY2013, we fully designed and built all necessary components for the blue-green chaotic CLIDAR source (infrared chaotic laser, fiber preamplifier, fiber gain amplifier, and frequency doubler) and have integrated them into a working CLIDAR transmitter (Task 3). We also have begun using the transmitter to conduct system experiments to demonstrate and explore the CLIDAR's performance in underwater environments (Task 2).

The completed CLIDAR transmitter operates at 150 mW continuous output power at 532 nm. The intensity modulation signal of the output is chaotic, with instantaneous wide bandwidth of at least 3 GHz. This transmitter consists of a low-power chaotic infrared fiber laser source, two fiber amplifier stages, and a frequency doubler to convert the wavelength from 1064 nm to 532 nm. Custom computer code has been developed to solve the rate equations governing rare-earth doped fiber lasers and amplifiers, and this code has been used to design the laser and amplifiers for the CLIDAR transmitter. This code has also been packaged and published as a design toolbox for use by the research community, and has downloaded several hundred times to date. Using the CLIDAR transmitter, ranging has been performed in a water tank, where 8 mm accuracy and +/-4 cm resolution has been demonstrated, as limited by the receiver's sampling speed and analog bandwidth. Since the signal is non-repeating, the range measurements are also unambiguous. These results were obtained in clean water, and investigation of the system performance in turbid water is now underway.

Detailed Progress Report

The following progress will be described below:

1. CLIDAR Transmitter
    a. Design
    b. Performance
    c. Simulation of Fiber Laser and Amplifiers
2. Ranging using CLIDAR Transmitter

CLIDAR Transmitter: Design

The chaotic LIDAR (CLIDAR) transmitter delivers a >1 GHz chaotic signal at 150 mW at 532 nm. This optical source is designed for underwater lidar and has the following features:

- Wide bandwidth, for high resolution ranging.
- Nonlinear chaos, for non-repeating unambiguous ranging.
- High powers, for long standoff ranges.
- Operation at blue-green, to minimize absorption.
- High frequency, to allow suppression of backscatter.

To achieve these design goals, several components must be integrated:

- Chaotic fiber laser, with non-repeating, wideband, high frequency modulation.
- Fiber amplifiers, generating multi-watt infrared powers.
- Frequency doubler, converting the infrared to a blue-green signal.

This design concept is shown in Figure 1, and a detailed design is given in Figure 2.

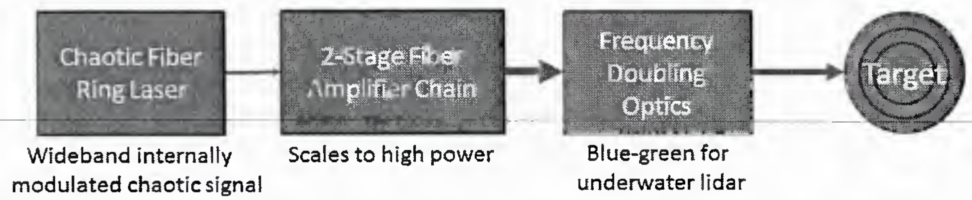
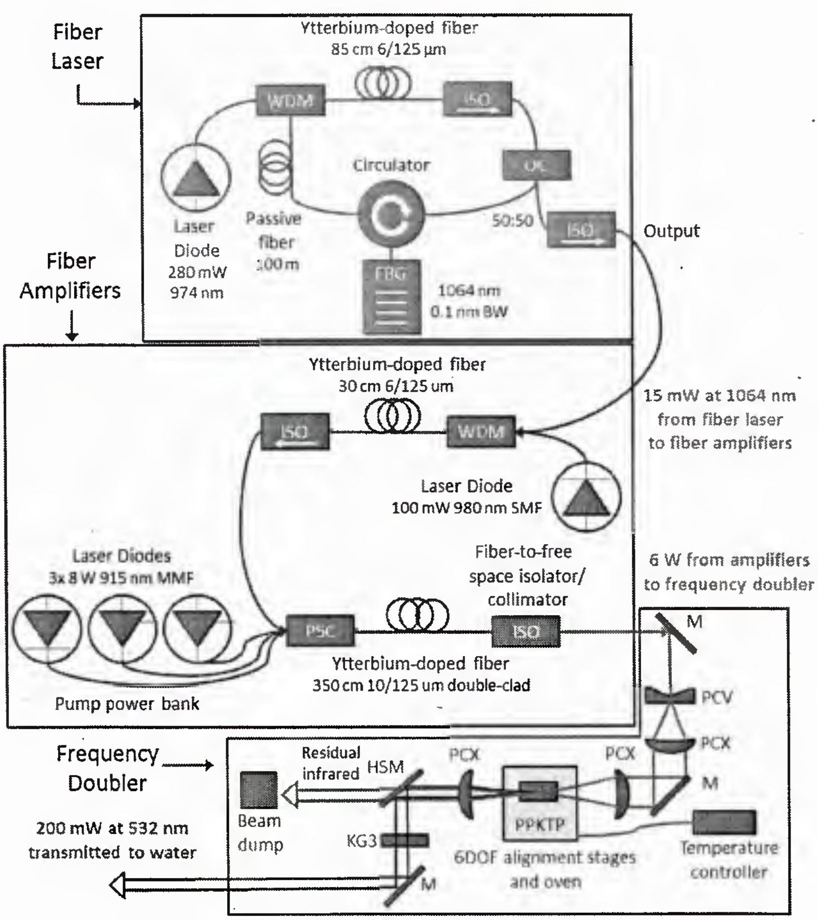


Fig 1. CLIDAR Transmitter Design. The transmitter is designed for underwater lidar in absorptive, scattering underwater environments; it consists of a fiber laser, two fiber amplifier stages, and a frequency doubler.



WDM: Wavelength-division multiplexer; ISO: Isolator; OC: Output coupler; FBG: Fiber Braggs grating; PCV: Plano-concave lens; PCX: Plano-convex lens; PPKTP: Periodically poled KTP; HSM: Harmonic separator mirror; KG3: Glass infrared filter; M: Mirror

Fig 2. CLIDAR Transmitter Block Diagram. The transmitter delivers a >1 GHz chaotic signal at 532 nm with >150 mW continuous output power.

CLIDAR Transmitter: Performance Overview

The CLIDAR transmitter's wideband, high frequency chaotic signal is generated by the intensity modulation of a 1064 nm ytterbium-doped fiber laser (YDFL). This modulation is completely internal and is determined by the cavity physics, so that no signal generator or electro-optic modulator are needed. The modulation obtained extends at least to 3 GHz (measurement limited by the bandwidth of the spectrum analyzer used). The power spectral density is made to be flat by adjusting the active fiber length, and incoherent mode competition is encouraged by adding a 100 m passive fiber to the cavity, greatly increasing the number of simultaneously resonating modes. By these modifications, a noise-like chaotic signal is obtained, which has an easily resolved, non-repeating, thumbtack

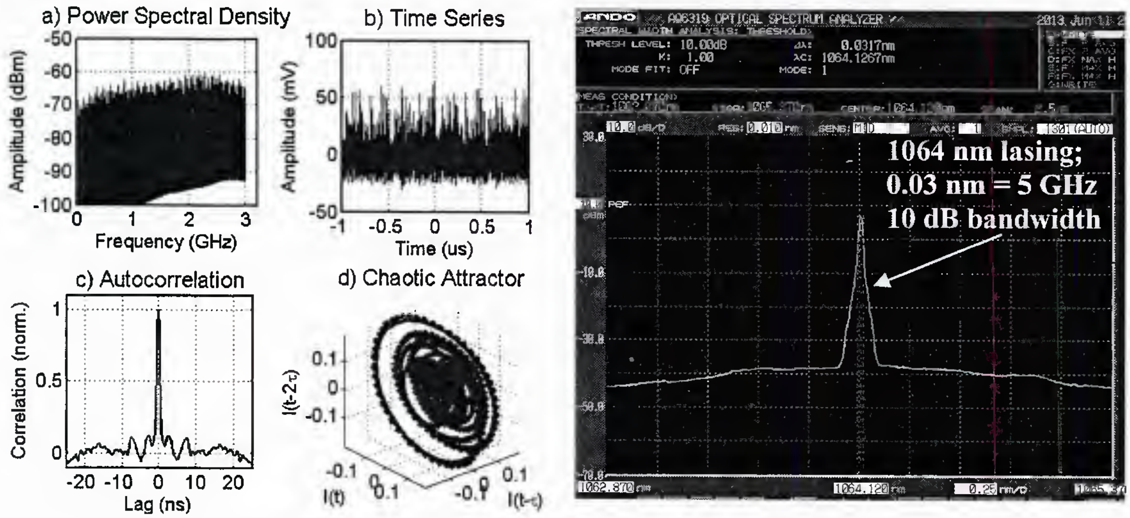


Fig 3. Output of the fiber laser. [*Left panel*] *Top left*: The frequency spectrum extends to 3 GHz, with a flat envelope. *Top right*: the modulation output is noise-like and non-periodic. *Bottom left*: the autocorrelation is a sharp non-repeating thumbtack function. *Bottom right*: a distinctive attractor pattern is indicative of deterministic chaos. [*Right panel*] Optical spectrum showing 0.03 nm (5 GHz) 10 dB bandwidth.

autocorrelation function that is well-suited for ranging. The YDFL signal's wide, flat spectrum, noiselike trace, sharp autocorrelation peak, and chaos are shown in Figure 3.

The YDFL outputs 15 mW power at 1064 nm. Since watt-level infrared powers are necessary for efficient frequency doubling, two fiber amplifiers are used to boost the signal to 40 mW, and then to 6 W. The signal then leaves the fiber and is passed through the frequency doubling crystal, which outputs 150 mW light at 532 nm. The single-pass crystal conversion efficiency of 3% is consistent with the expected efficiency of 4% at these power levels, and output power level is sufficient to perform system experiments in turbid waters. In the next section, the design of the amplifiers and laser will be presented.

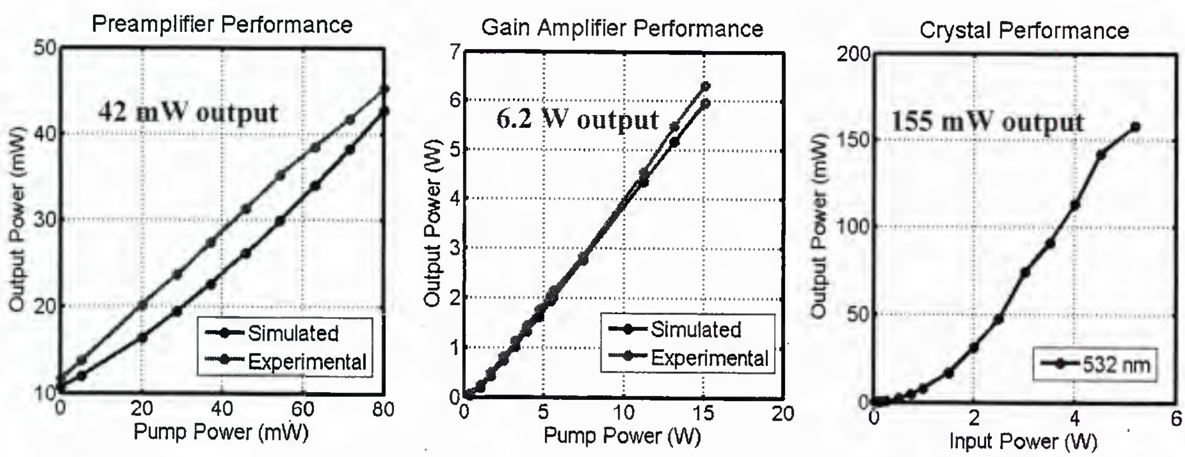


Fig 4. Output of the fiber amplifiers (preamplifier and gain amplifier) and frequency doubler (crystal).

CLIDAR Transmitter: Simulation of Fiber Lasers and Amplifiers

Both analytical and numerical calculations were used to design the fiber lasers and amplifiers. These calculations predicted the power distribution through the fiber, the operating wavelengths, and noise due to spontaneous emission. Custom computer codes solved the rate equations governing the ytterbium dopant, and accounted for the geometry and loss of each component in the system.

Analytical calculations were sufficient for qualitative optimization of the fiber laser parameters (i.e. choosing coupler reflectances, pump powers, and fiber lengths), but for the amplifiers, nonlinear saturation effects came into play, and numerical simulations were developed. By using a modified Lax-Wendroff central-difference scheme to solve the one-way-wave equations with second order accuracy in time and space, we developed a fast solver that could simulate the amplifiers in a few seconds. Using this solver we were able to make design predictions quickly to support and validate the experiments. These programs have been packaged in a "Fiber Lasers and Amplifiers Toolbox", posted on Matlab's website, and accessed by hundreds in the research community. This software allows us to rapidly generate new fiber laser and amplifier designs for a variety of situations.

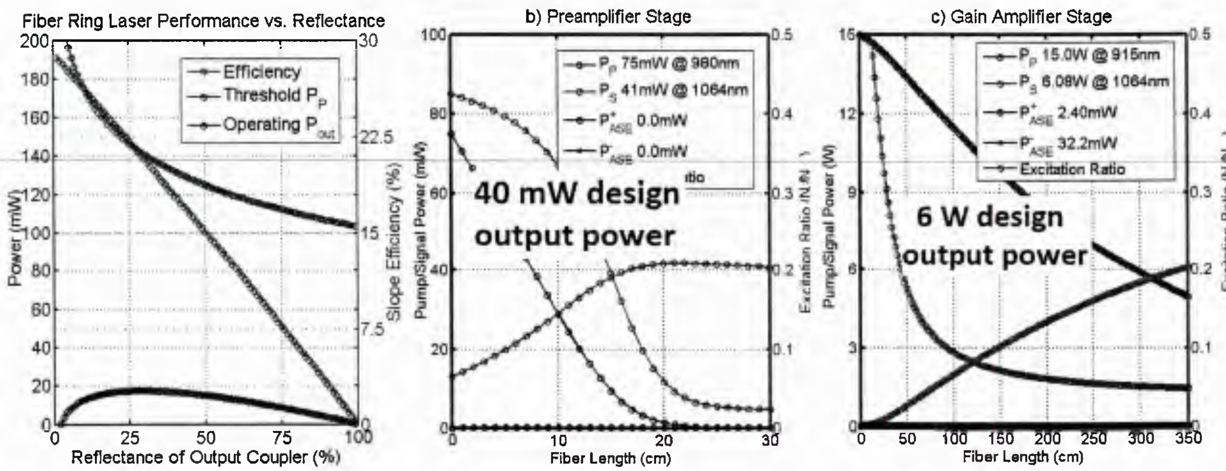
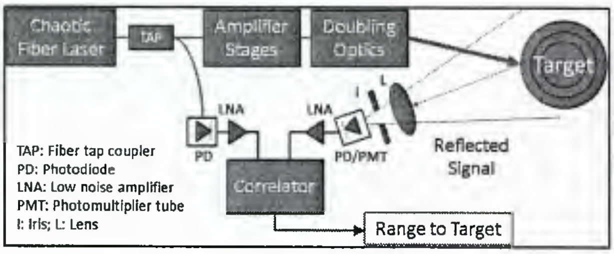


Fig 5. Fiber laser and amplifier simulations. *Left*: Analytical calculations allowed optimization of fiber laser parameters; here performance is shown against reflectance. *Middle*: Numerical simulations predicted the distribution of pump and signal powers throughout the fiber, here for the preamplifier. *Right*: Numerical simulations allowed performance prediction for various pump and signal input powers, fiber types, and fiber lengths, here for the gain amplifier.

Ranging Experiment using the CLIDAR Transmitter

We performed a preliminary ranging experiment underwater to test the CLIDAR transmitter and baseline its performance. Translating a mirror back and forth in a small water tank, we demonstrated that the system can unambiguously resolve the range to an underwater target, with good accuracy and high resolution. The average error observed was 8 mm, while the range resolution averaged +/- 4 cm, with no range ambiguity observed. We note that this performance is receiver limited: the error is limited by the 5 GSPS sampling speed of the digitizer, and the resolution by the analog bandwidth of the digitizer. Follow-on experiments will be conducted with a diffuse target and varying turbidity. It should also be noted that a Labview program has been developed to automate the experiments. The Labview graphical user interface is shown in Figure 9. This custom interface performs sub-second data acquisition and processing for real-time ranging and water profiling measurements.



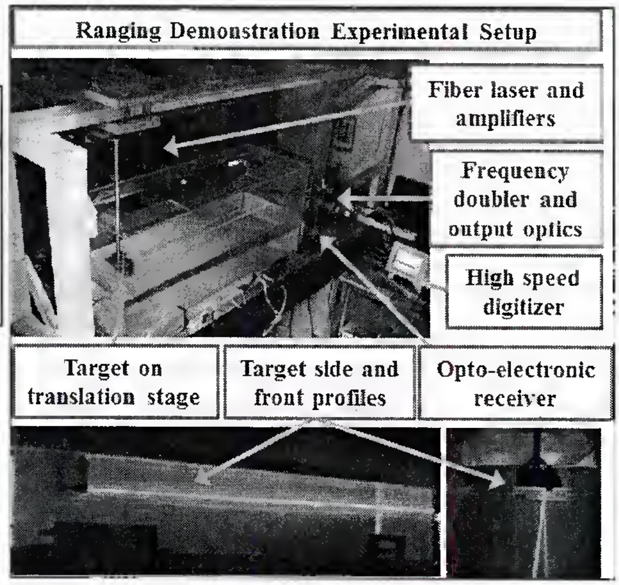


Fig 7. Ranging demonstration setup. *Top*: Block diagram of CLIDAR ranging. *Right:* The CLIDAR system (behind the tank) uses the 532 nm chaotic signal to determine the range to the target.

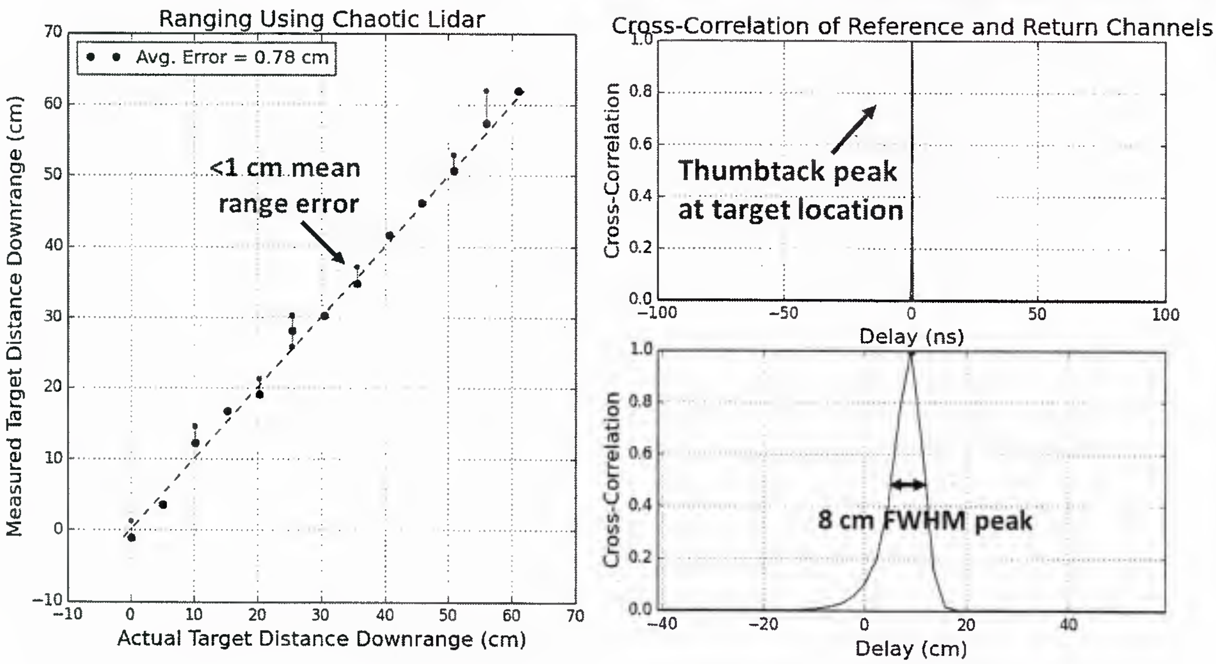


Fig 8. Ranging demonstration results. *Left*: Actual versus target range showing an average error of <1 cm. *Top right:* The target peak is a sharp and unambiguous thumbtack. *Bottom right:* Zooming in on the target peak, the resolution is seen to be +/- 4 cm full width half maximum (FWHM).

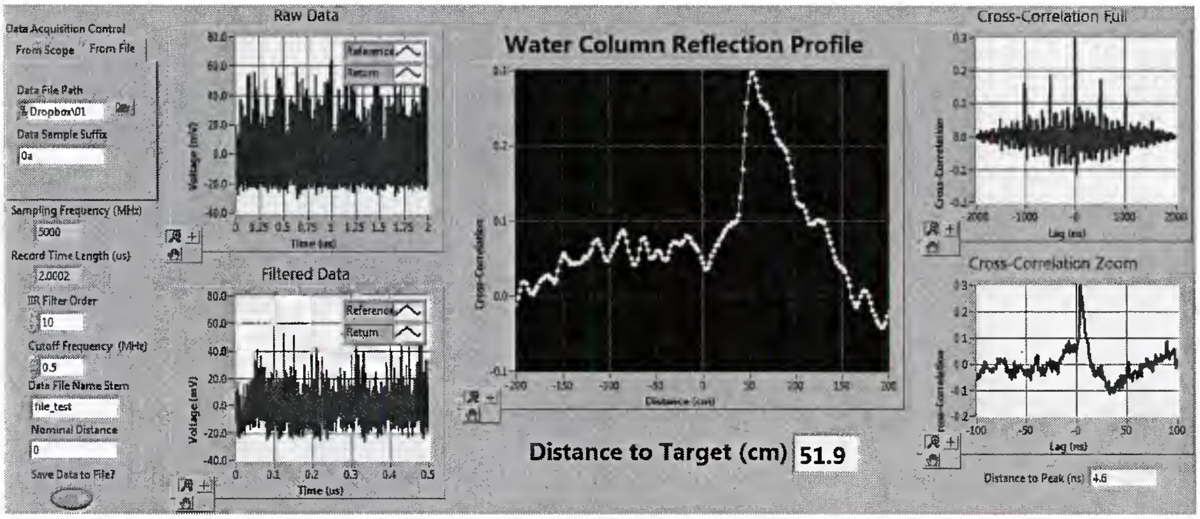


Fig 9.CLIDAR control software. This custom interface performs sub-second data acquisition and processing for real-time ranging and water profiling measurements.

Publications

[1] LK Rumbaugh, EM Bollt, Y Li, WD Jemison. "A 532 nm Chaotic Lidar Transmitter for High Resolution Underwater Ranging and Imaging." In *OCEANS 2013, MTS/IEEE San Diego*, Sept. 2013.

[2] LK Rumbaugh, WD Jemison, Y Li, and TA Wey. "Wide Bandwidth Source for High Resolution Ranging." In *Ultra-Wideband (ICUWB), 2012 IEEE International Conference on*, pages 482–485. IEEE, Sept. 2012.

Short Work Statement for FY14

1. Explore CLIDAR Performance in Various Turbidities
2. Investigate Possible System Performance Improvements
3. Dynamic Simulation of Chaotic Fiber Ring Lasers

<u>Explore CLIDAR Performance in Various Turbidities</u>

The ranging experiment described was conducted in relatively clear water (c=1.0/m) at round-trip distances between 0.4 and 1.6 m, so performance is demonstrated only at 0.4 to 1.6 attenuation lengths. Also, little scattering was observed in this test. Tests in highly turbid water are underway, which will show CLIDAR's performance at ranges of 2 to 10 attenuation lengths and in scattering environments using diffuse targets.

<u>Investigate Possible System Performance Improvements</u>

The system power is currently limited by the conversion efficiency of the frequency doubler. This efficiency may be improved either by increased infrared power, or by a multi-pass resonator. Either approach could result in an order-of-magnitude improvement in output power, which may be desirable if operation at >10 attenuation lengths is required.

<u>Dynamic Simulation of Chaotic Fiber Ring Lasers</u>

An additional focus area is dynamic simulation of these chaotic fiber ring lasers, which would build on the steady-state numerical simulations performed to date. Such a simulation could predict laser behavior to include signal bandwidth and nonlinear chaos, and would allow the design and tailoring of these lasers for high performance underwater. A dynamic simulation would have to include both polarizations of the circulating electromagnetic wave, and so would be both complex and computationally intensive; however, the efficient simulation algorithms developed to date may make these calculations feasible.

Clarkson UNIVERSITY defy convention

Chaotic LIDAR for Naval Applications
N000141010906

ONR Revolutionary Research . . . Relevant Results

Objective:

Investigate chaotic LIDAR for high resolution underwater imaging and ranging.
•Develop a blue-green wideband chaotic laser to support scientific experiments
•Perform system-level investigations into the underwater propagation/scattering characteristics chaotic laser signal in order to determine the range resolution/accuracy and backscatter suppression that can be expected from this approach

Approach:

- Create optical chaos by using long-cavity infrared fiber lasers to support many simultaneous lasing modes
- Amplify the infrared chaotic signal using a two-stage fiber amplifier to achieve sufficient optical power for doubling.
- Use a PPKTP crystal for frequency doubling to the blue-green wavelengths desired for underwater operation
- Integrate all components into a chaotic lidar transmitter and use it to conduct system experiments to explore the potential of chaotic lidar for underwater applications.

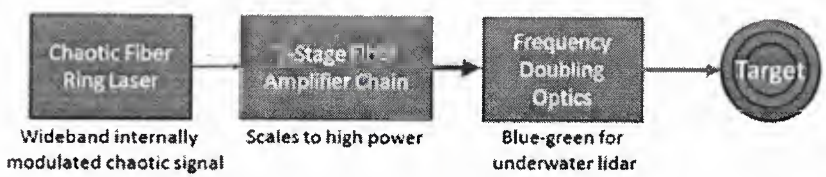
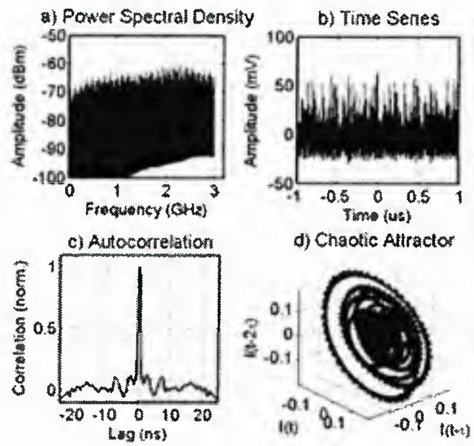
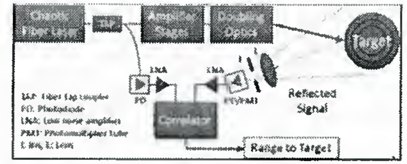
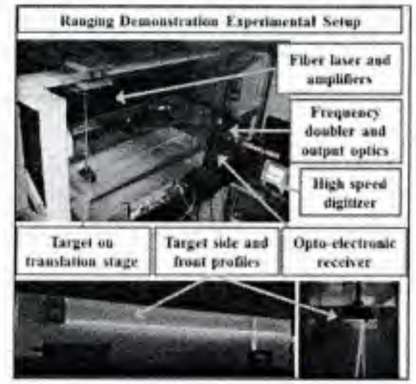


Figure:

A blue-green chaotic laser transmitter has been built and system experiments have been initiated







Scientific or Naval Impact/ Results:

- Successfully designed, built, and integrated a wideband (~ 3GHz) 150 mW chaotic blue-green laser transmitter.
- Developed a custom "Fiber Lasers and Amplifiers" MATLAB toolbox that performs efficient numerical simulations of fiber lasers and fiber amplifiers.
- Achieved receiver-limited 8 mm accuracy and +/-4 cm unambiguous range resolution in a proof-of-concept underwater ranging experiment.
- Currently designing experiments to characterize chaotic lidar ranging performance and backscatter suppression in turbid water.